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**Park et al.**

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(54) **TUNABLE SEMICONDUCTOR LASER AND METHOD THEREOF**

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(62) Division of application No. 10/744,457, filed on Dec. 22, 2003, now Pat. No. 7,065,108.

(30) **Foreign Application Priority Data**

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(51) **Int. Cl.**  
**H01L 21/00** (2006.01)

(52) **U.S. Cl.** ..... **438/22; 438/29; 438/31**

(58) **Field of Classification Search** ..... **438/22, 438/29, 31**

See application file for complete search history.

(57) **ABSTRACT**

A tunable semiconductor laser including a Fabry-Perot filter and an electrode array is disclosed. The propagation direction of the light beam in the cavity can be consecutively shifted applying electric field or current to the electrode and tuning can consecutively performed over the wide wavelength band by the consecutive shift of the angle of the intra cavity laser beam.

**11 Claims, 12 Drawing Sheets**

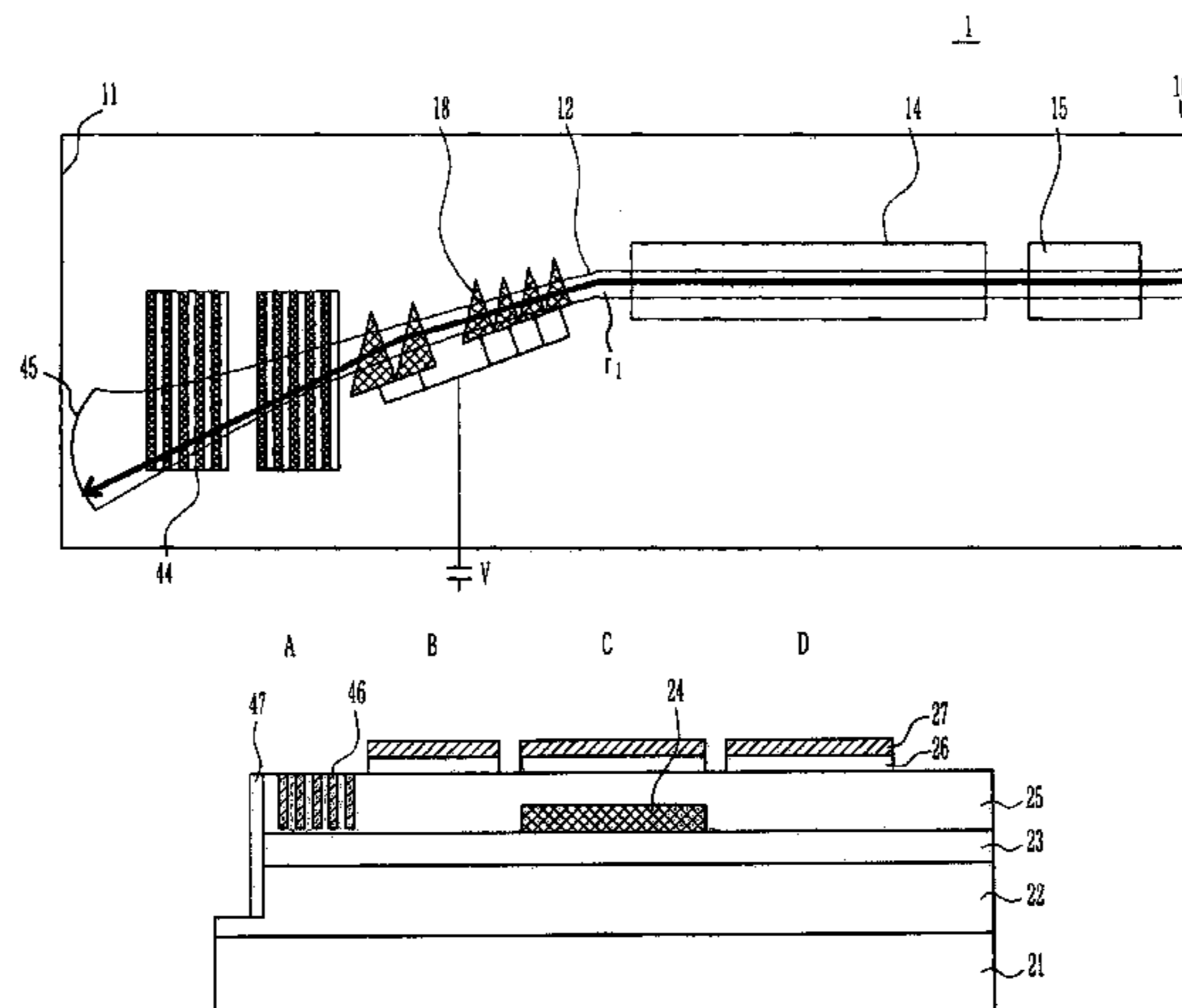


FIG. 1

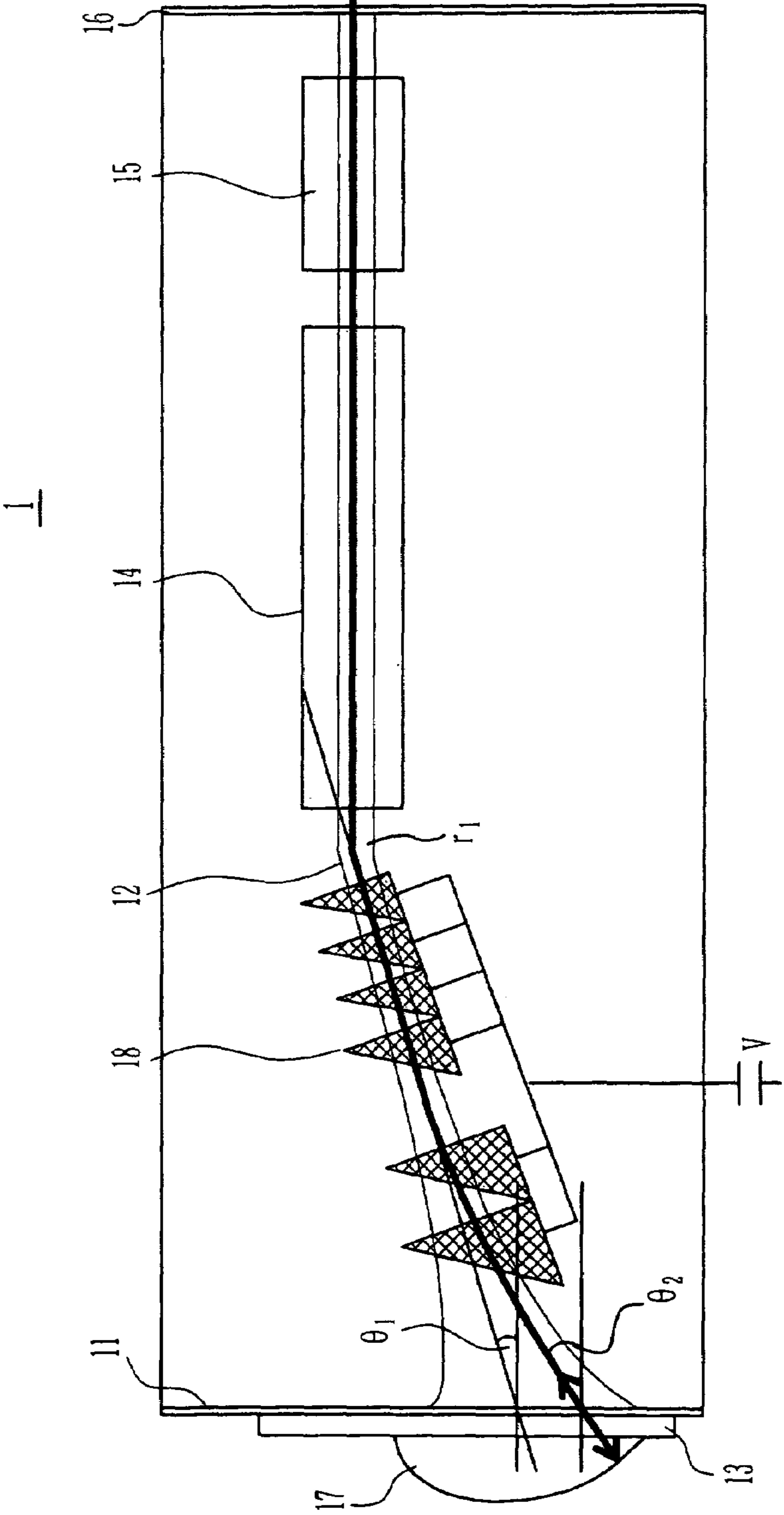


FIG. 2A

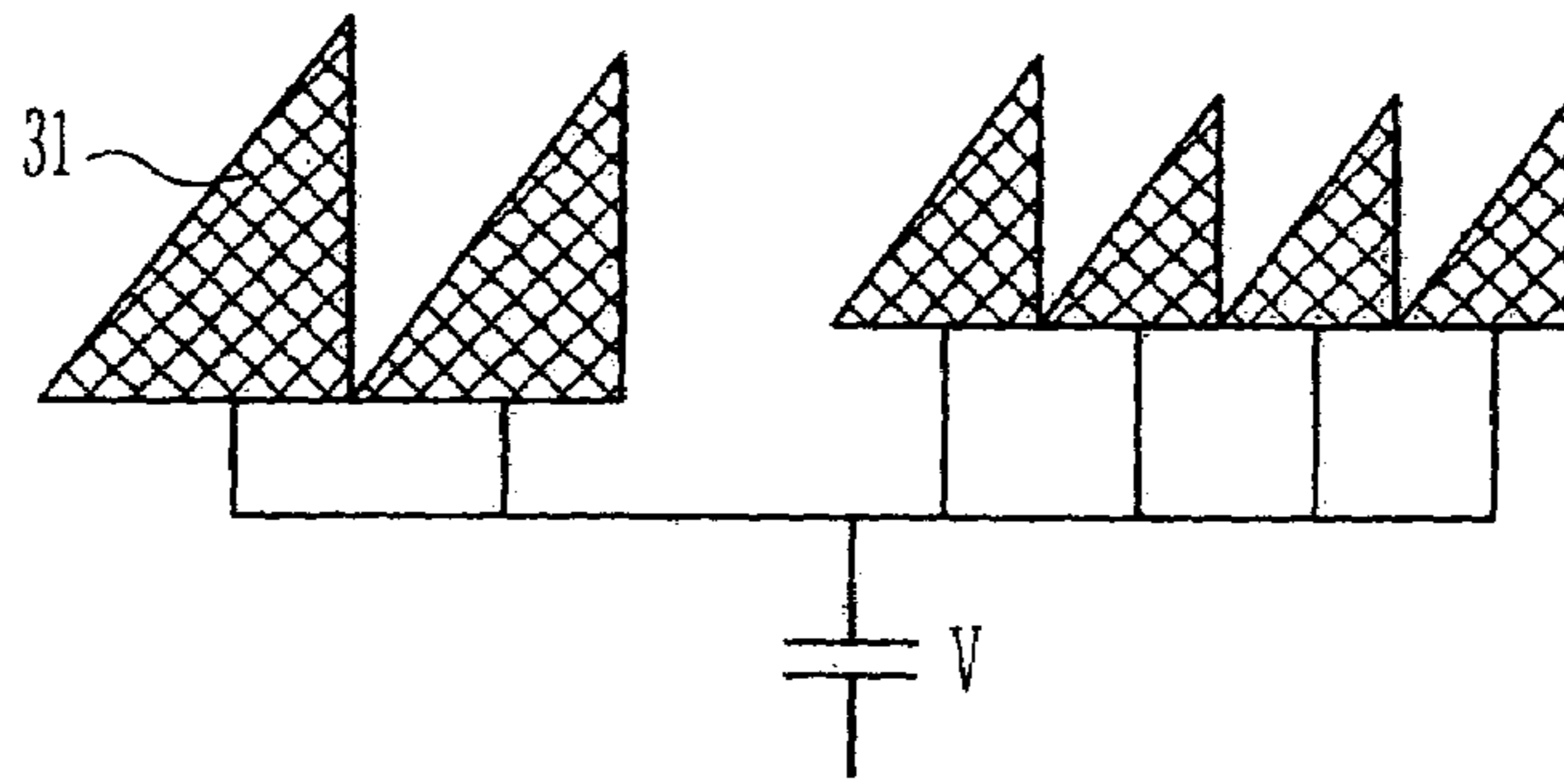


FIG. 2B

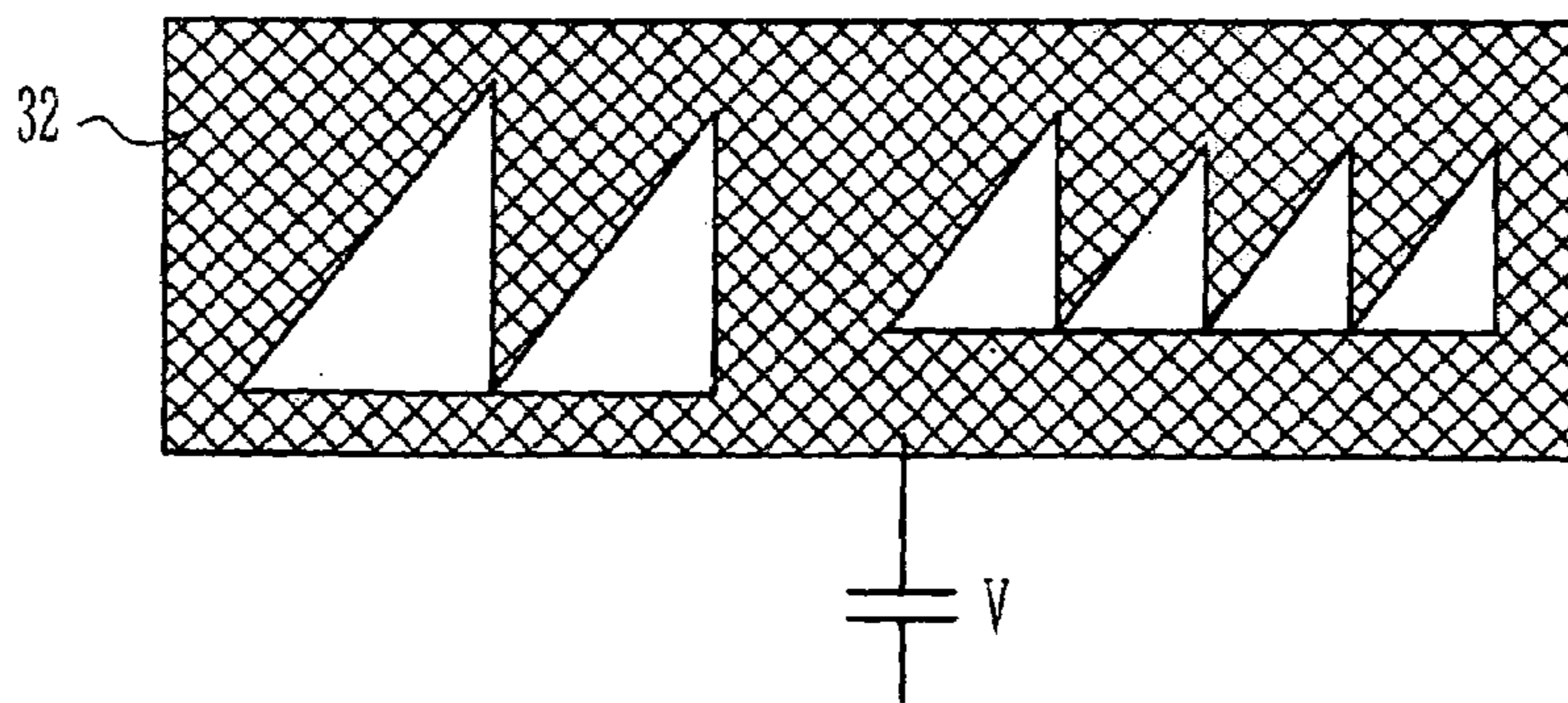


FIG. 3A

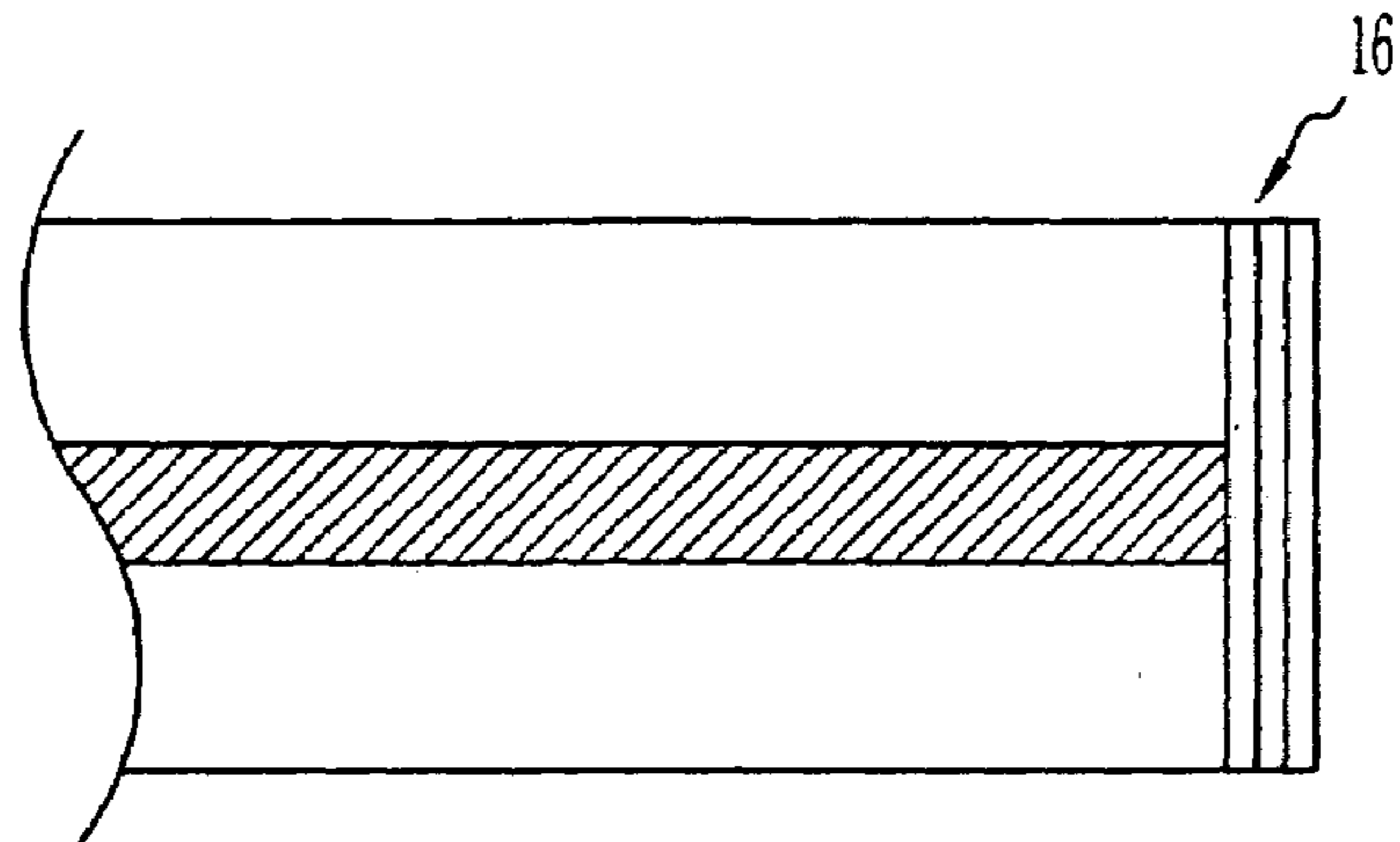


FIG. 3B

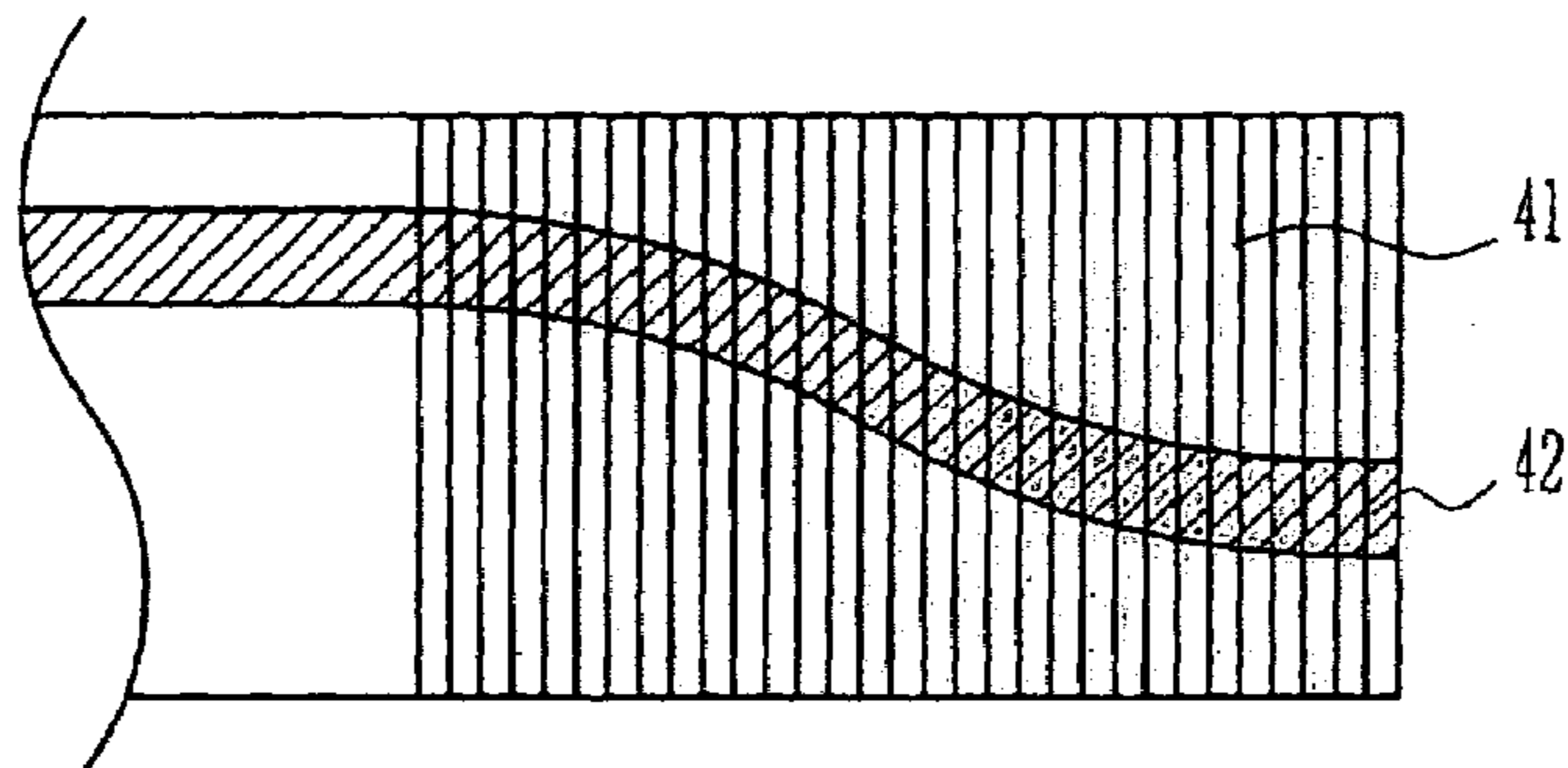


FIG. 3C

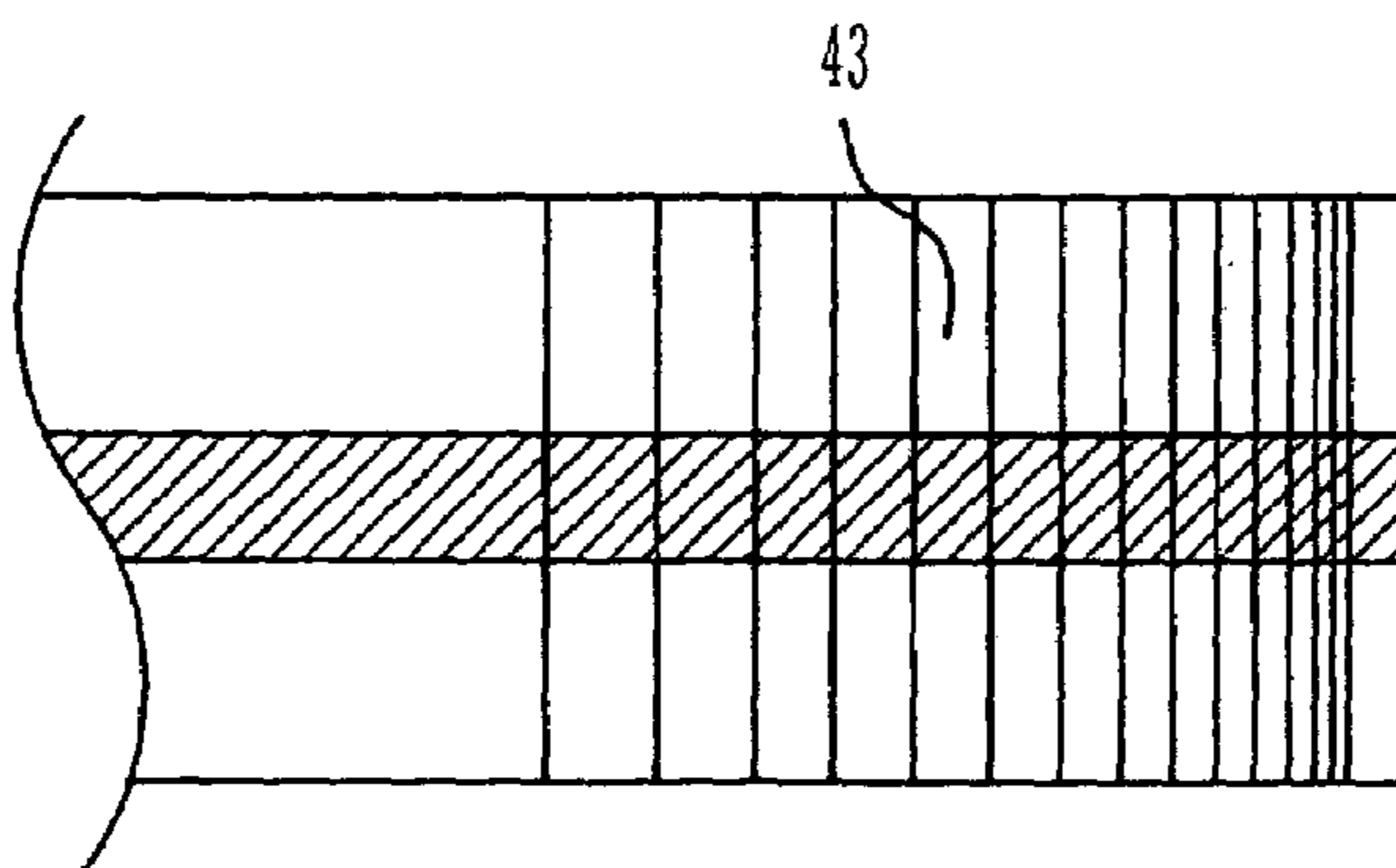


FIG. 4

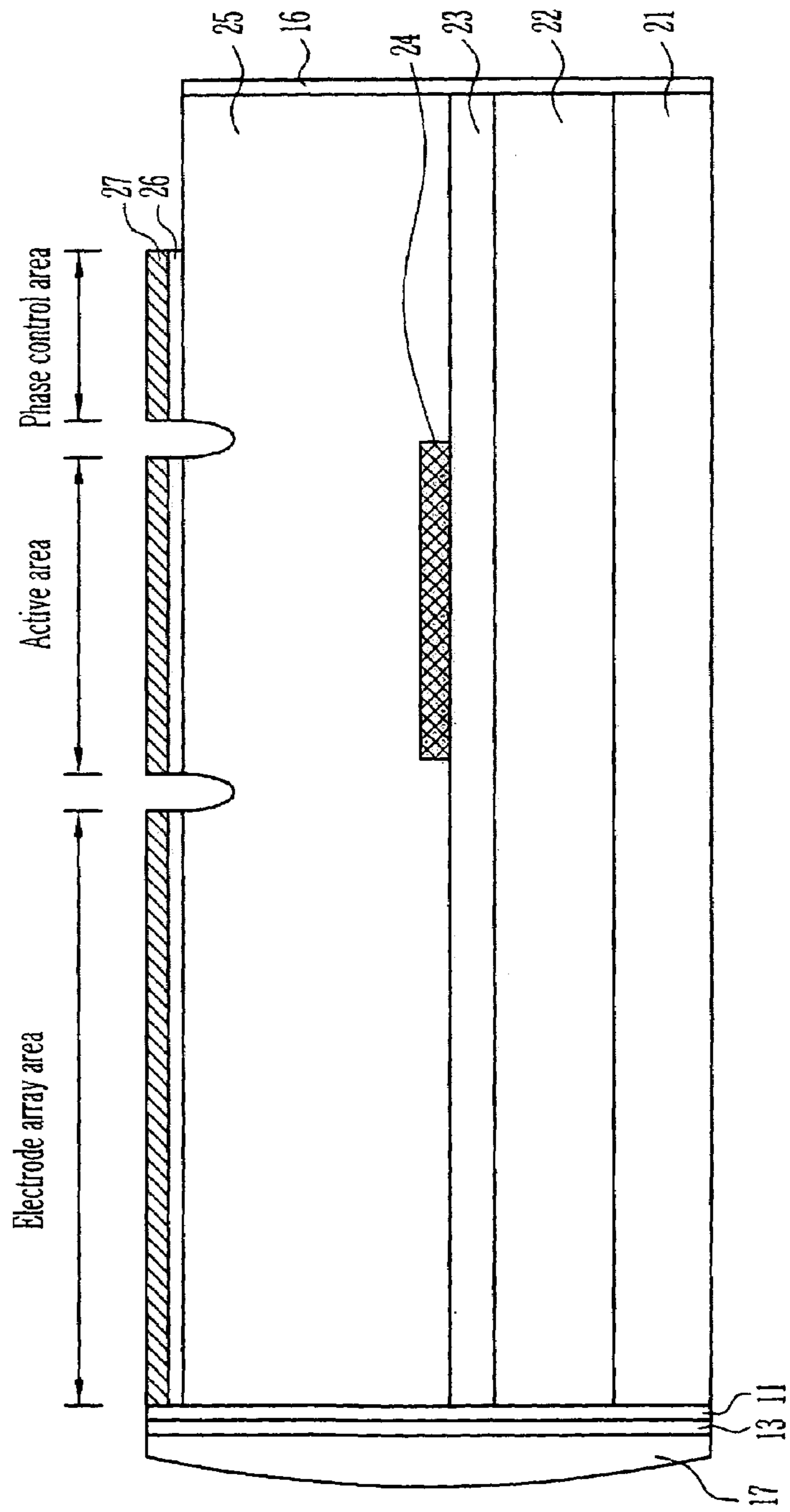


FIG. 5

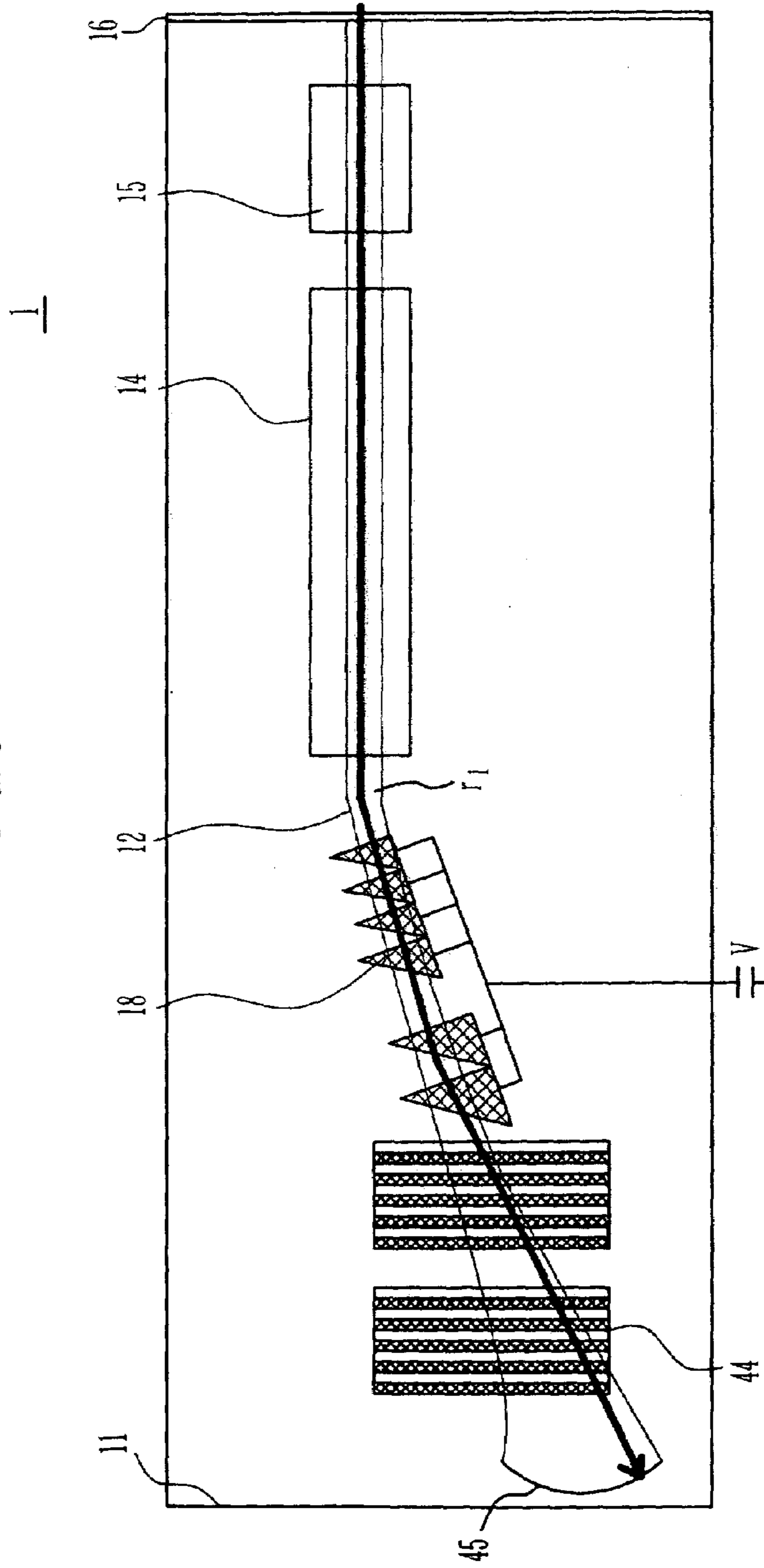


FIG. 6

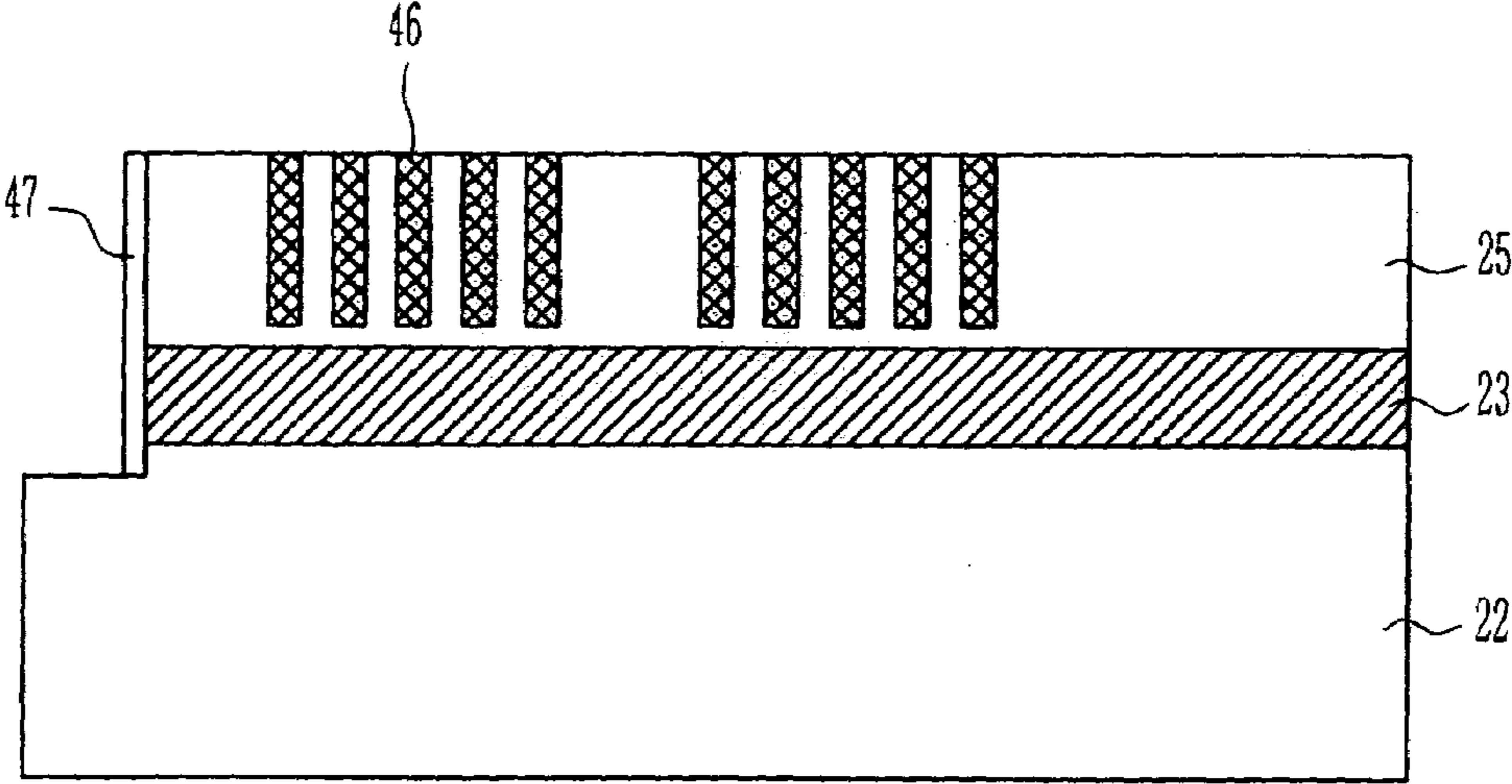


FIG. 7A

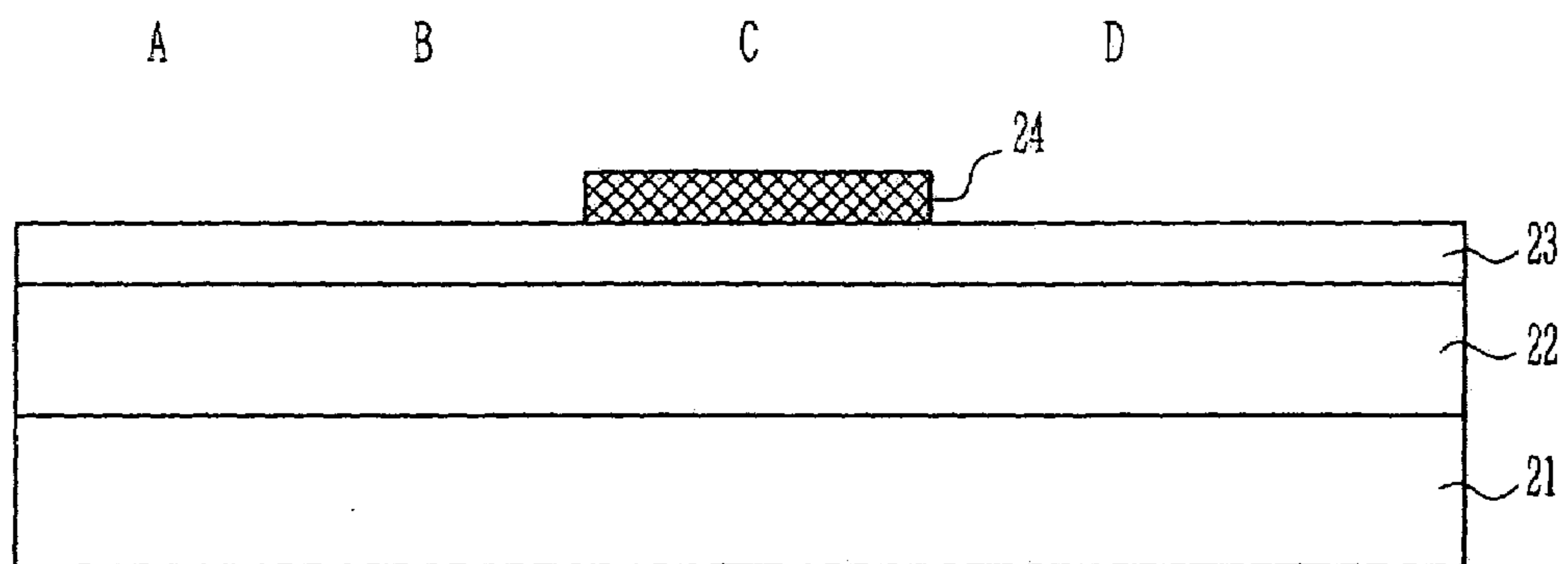


FIG. 7B





FIG. 8A

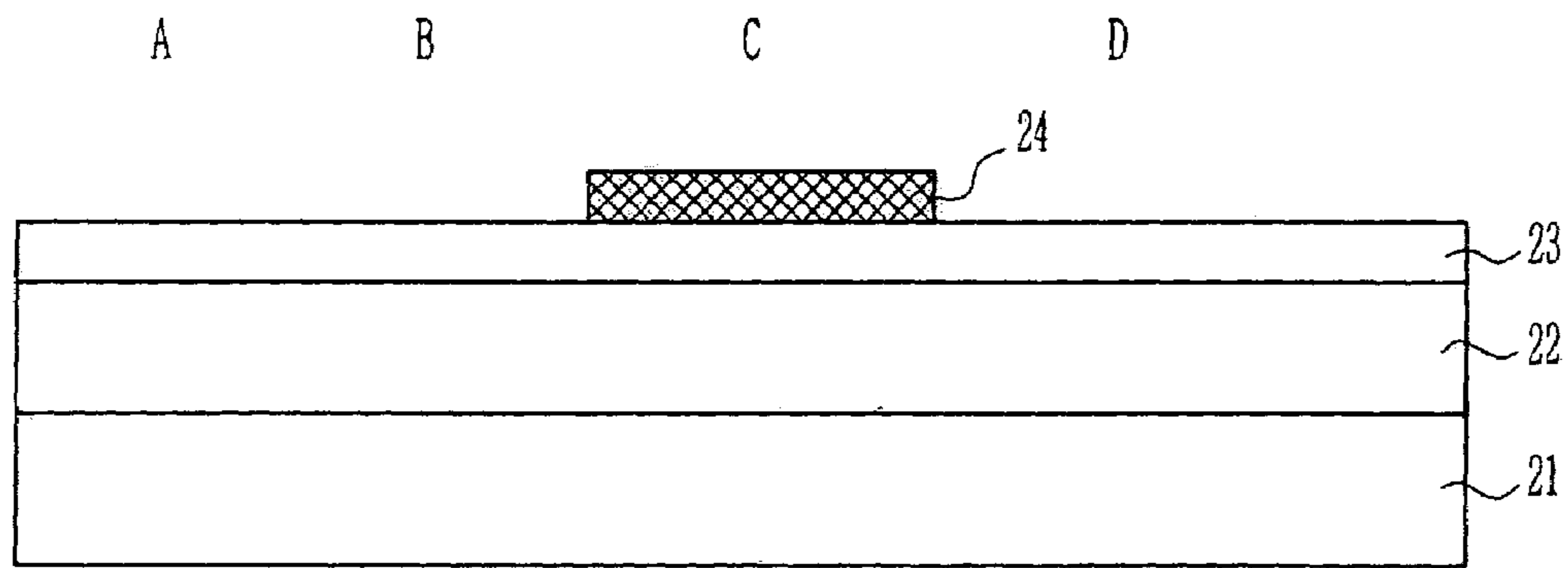


FIG. 8B

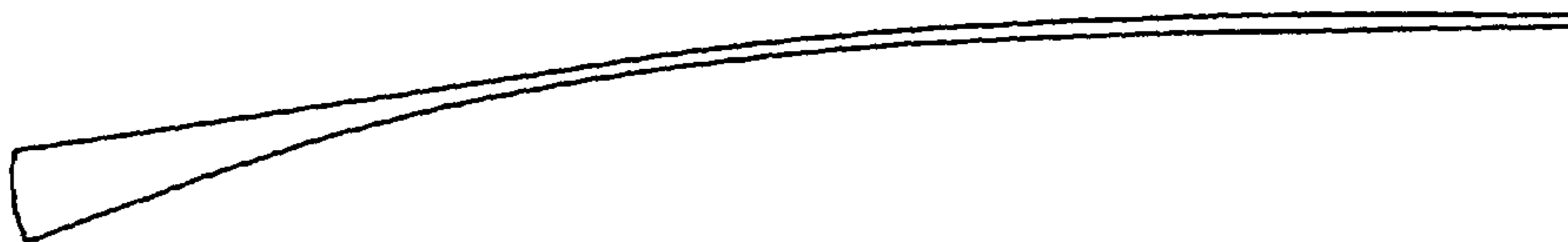


FIG. 9A

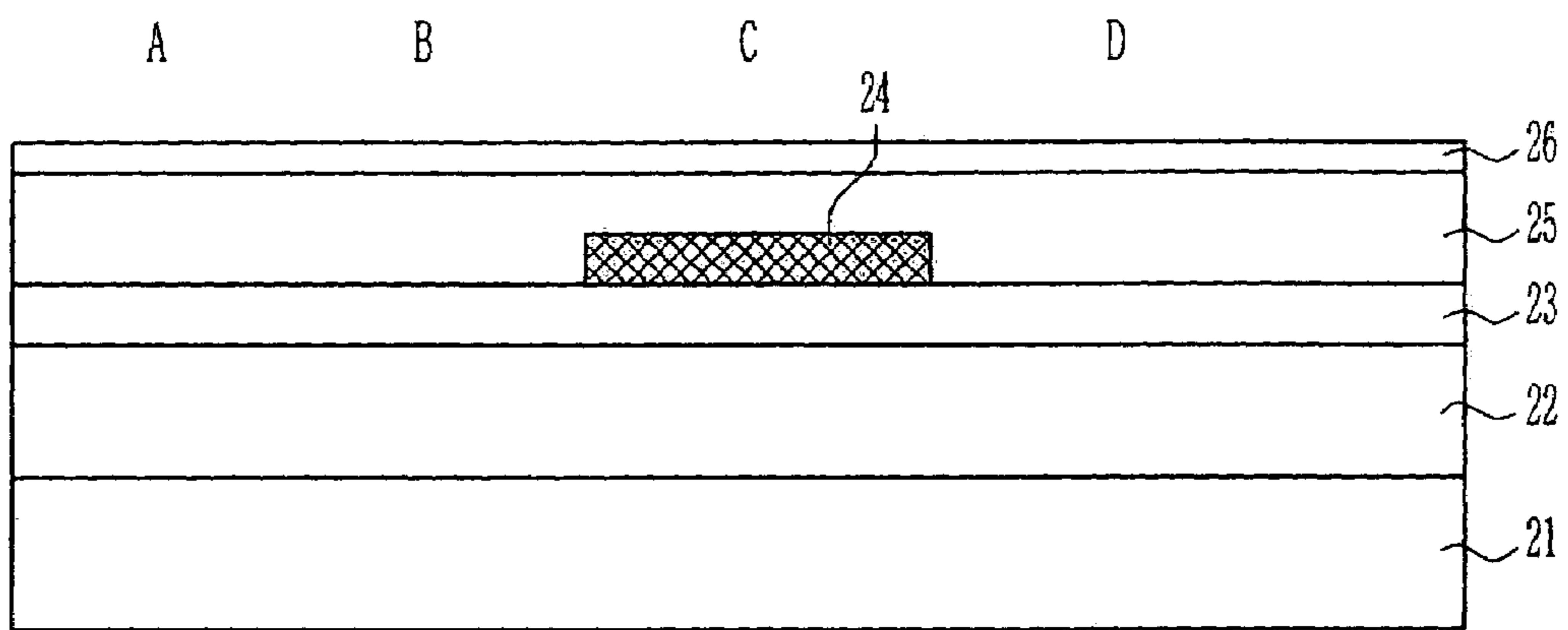


FIG. 9B

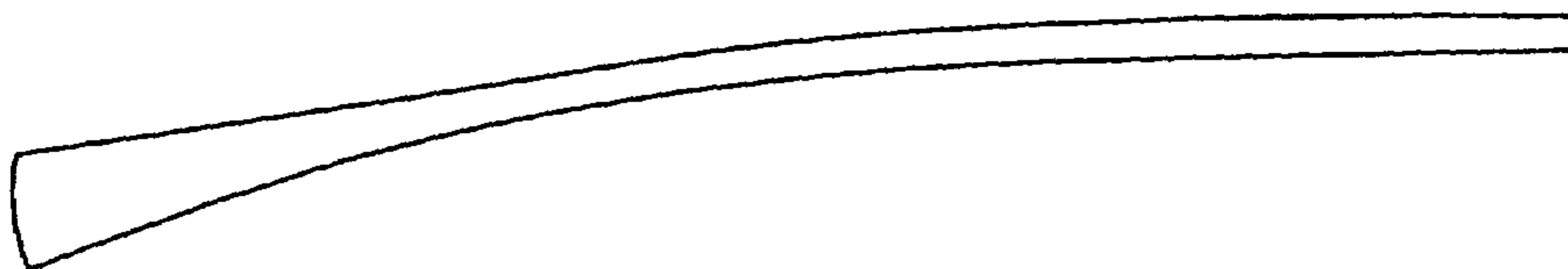


FIG. 10A

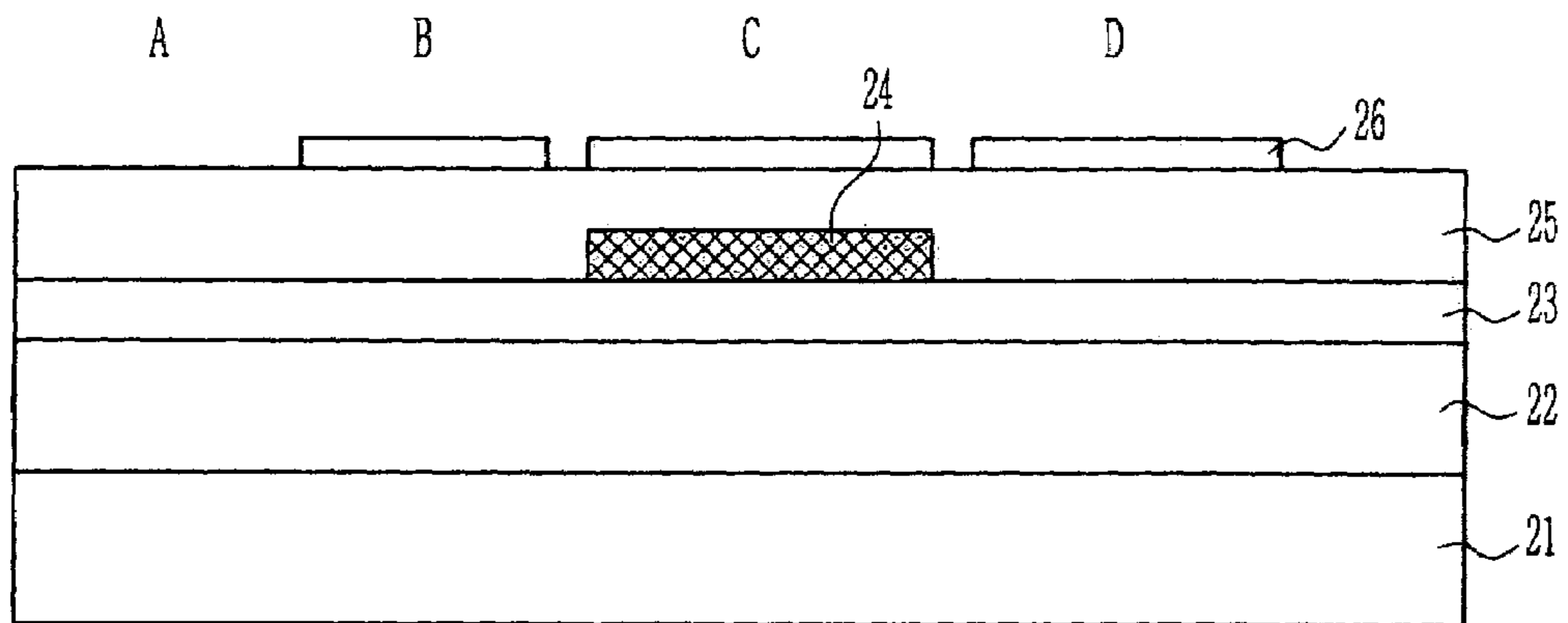


FIG. 10B



FIG. 11

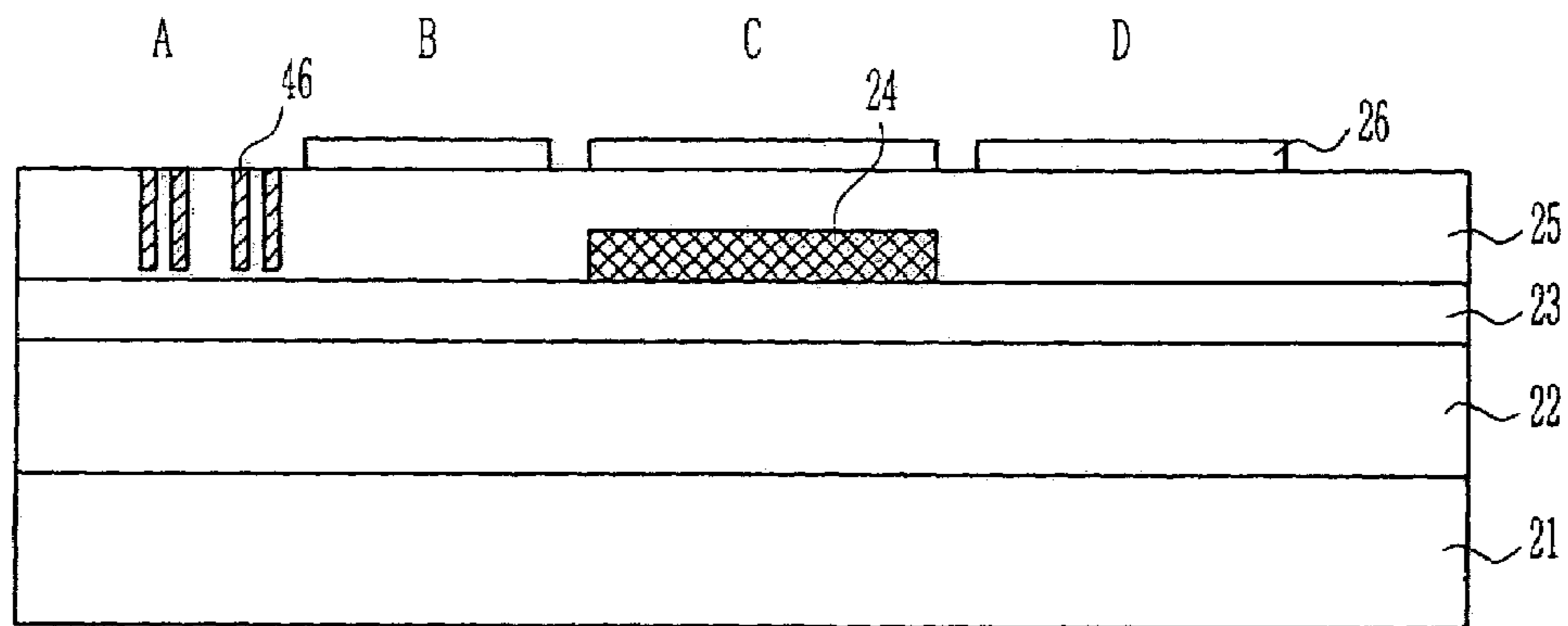


FIG. 12

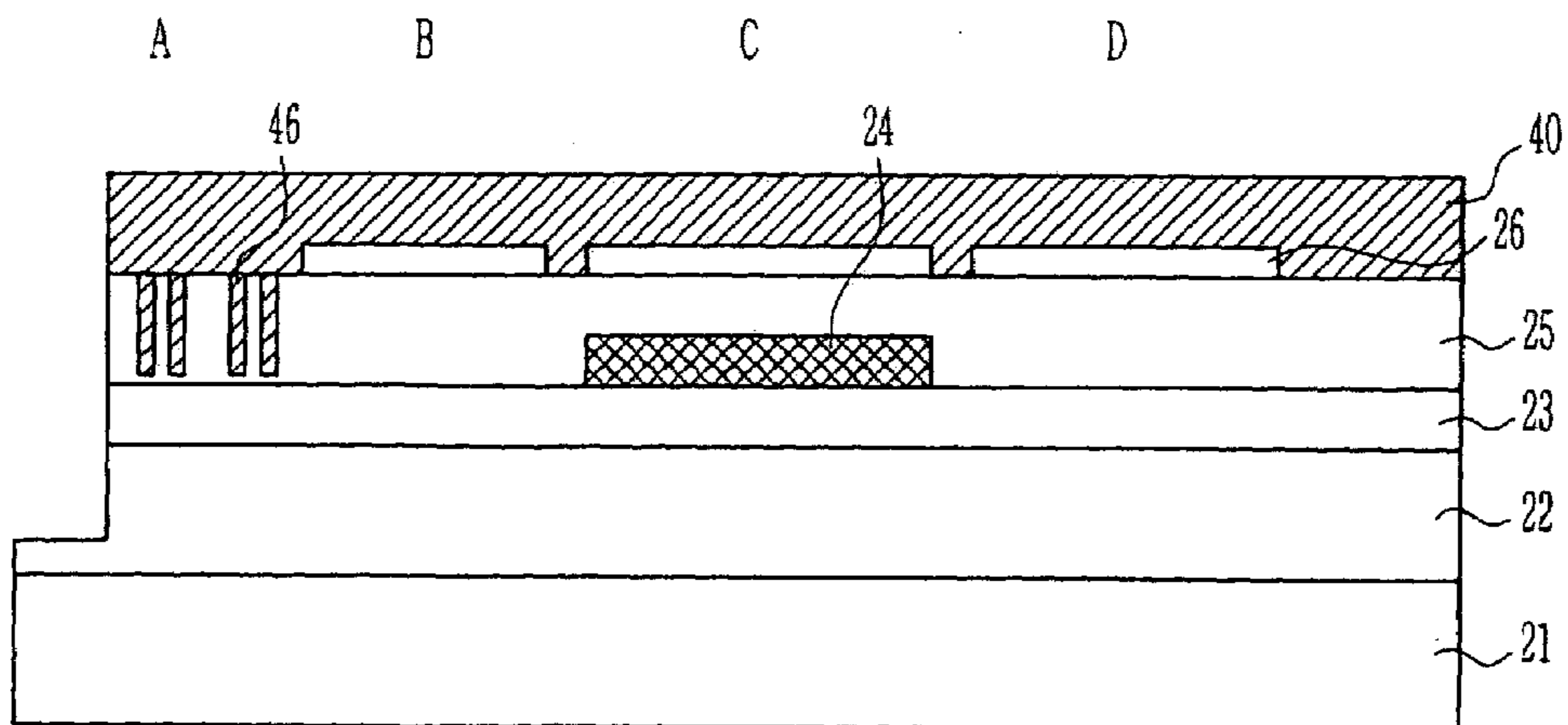


FIG. 13A

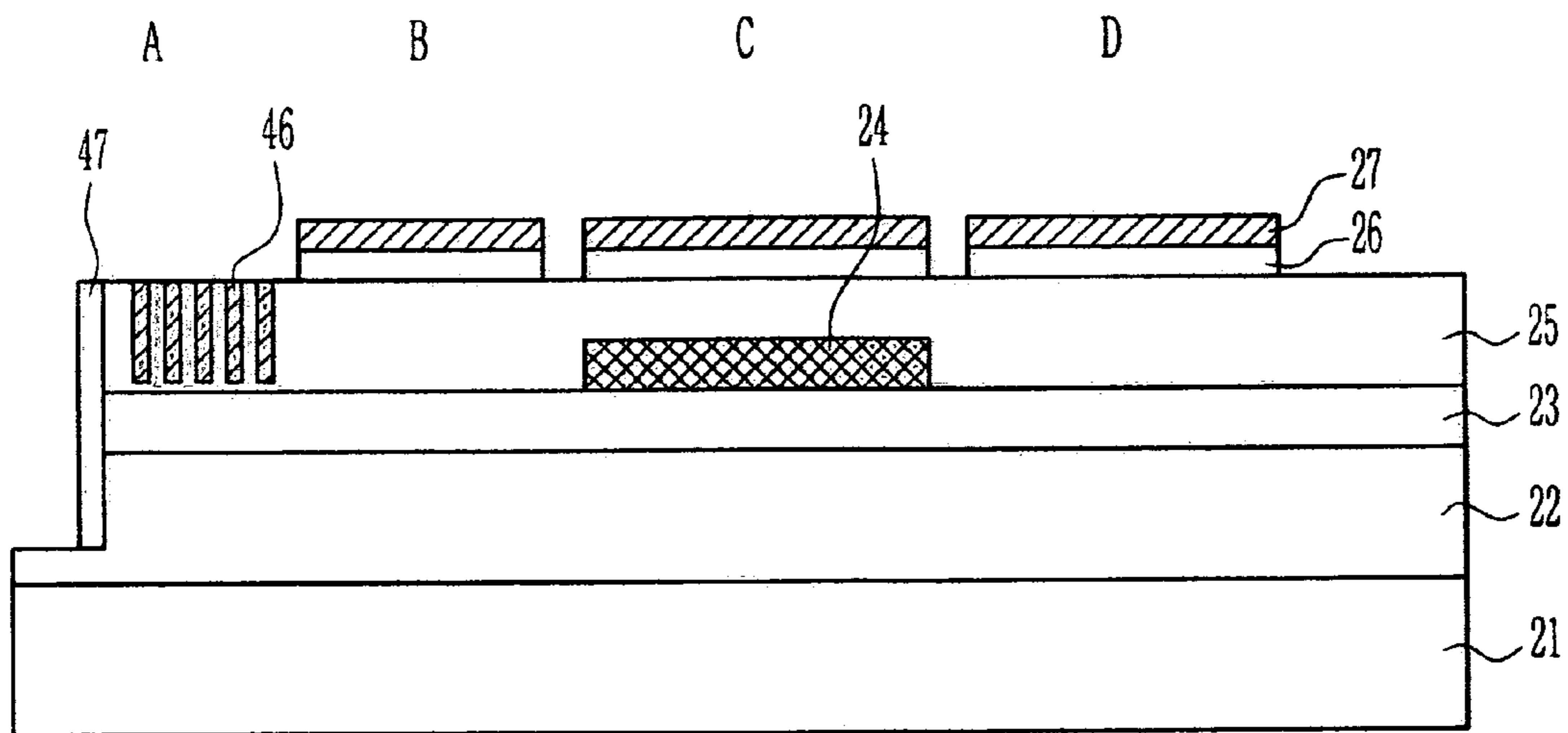
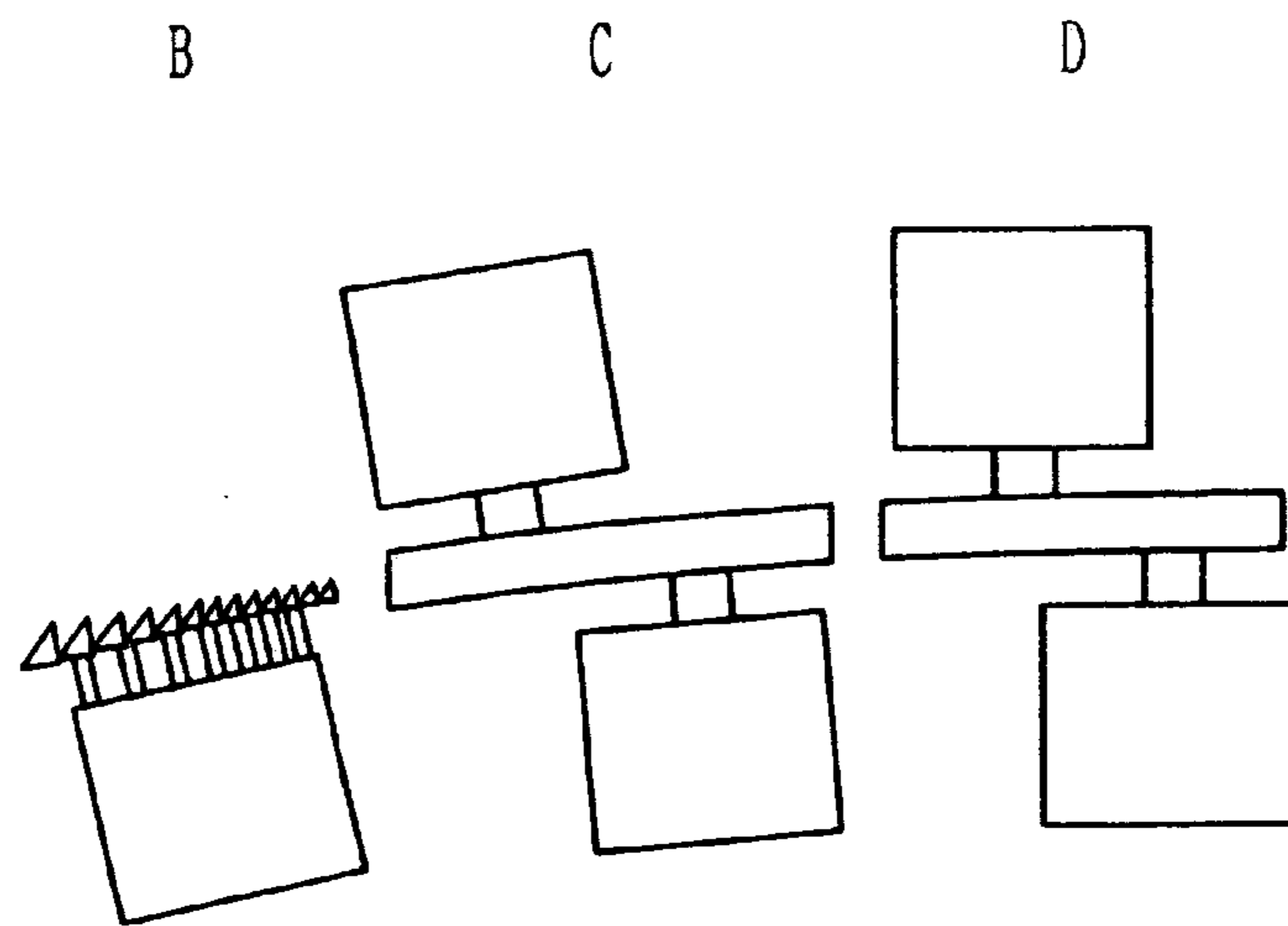


FIG. 13B



## TUNABLE SEMICONDUCTOR LASER AND METHOD THEREOF

The present patent application is a Divisional of Application No. 10/744,457, filed Dec. 22, 2003 now U.S. Pat. No. 7,065,108.

### FIELD OF THE INVENTION

The present invention relates to a tunable semiconductor laser, and more particularly, to a semiconductor laser that allows a very wide range of wavelength tuning over the optical fiber communication band.

### DESCRIPTION OF THE PRIOR ART

An explosive increase of information in the 80's and 90's has pushed the demand for an explosive increase of communication network capacity that requires many channels over a wide frequency range. The tunable semiconductor laser is a critical component in a wide variety of wavelength division multiplexing (WDM) and packet switching architectures. The network capacity in such systems increases in accordance with the number of wavelength channels accessible by the tunable laser transmitters.

The tunable semiconductor lasers are implemented, in most cases, by two different ways, non-monolithic and monolithic integrations.

The non-monolithic technique often employs the schemes of tunable solid state or dye lasers, which consist of active materials and tunable filters in the cavity mirrors. A typical example of non-monolithic external cavity tunable semiconductor laser consists of a piece of semiconductor that has a facet mirror at one end and a diffraction grating. The light beam oscillates directional coupler (GACC) filter. The tuning range depends on  $\Delta\mu/(\mu_1-\mu_2)$  rather than  $\Delta\mu/\mu$ , where  $\mu_1$ ,  $\mu_2$  are the effective refractive indexes of the two coupled optical waveguides. Although showing an impressive tuning range of 57 nm, this device has a primary limitation that increasing filter tunability by reducing  $(\mu_1-\mu_2)$  degrades the side mode suppression ratio. It has also been pointed out that the GACC has a very narrow design window to obtain an acceptable SMSR.

Up to the present, the most successful device available commercially is the semiconductor laser using a sampled grating (SG) DBR (U.S. Pat. No. 4,896,325). The sampled grating DBR provides periodic reflection maxima on the wavelength spectrum. Tuning is accomplished by shifting reflection peaks of two sampled gratings having a slightly different period from each other. Despite many advantages of SGDBR laser compared to other tuning schemes, it still has some fundamental shortcomings. The wavelength tuning is accomplished not continuously but, so called, quasi-continuously, which means that shifting from one wavelength to another arbitrary wavelength is very complicated and takes time. A user may tune to the only wavelengths defined by the provider of the device. As a slight modification to SGDBR laser, a new scheme of superstructure grating (SSG) DBR laser has been introduced, which uses chirped gratings instead of sampled gratings to produce the periodic reflection maxima (U.S. Pat. No. 5,325,325). This device not only shares the same problem of quasi-continuous tuning as SGDBR laser, but it also suffers from the fabrication difficulty requiring E-beam lithography, which may be a serious obstacle for mass production.

## SUMMARY OF THE INVENTION

Accordingly, in order to solve the above-mentioned problems, one object of the present invention is to provide a new scheme by which continuous tuning can be accomplished over a wide wavelength band for the semiconductor lasers.

Other object of the present invention is to remove some drawbacks of the current non-monolithic and monolithic semiconductor lasers and take their advantages thereof.

The further still other object of the present invention is to provide a tuning scheme over a wide wavelength range being capable of immediately applied to the optical fiber communication devices.

In order to accomplish the above-mentioned objects, a tunable semiconductor laser is comprised of a curve-shaped waveguide formed on a substrate for guiding light beam, an active area formed on a portion of the waveguide for generating the light beam, an electrode array formed at one side of the active area for changing the propagation direction of the light beam by applying electric field or currents to a predetermined portion of the waveguide, a Fabry-Perot filter for filtering the wavelength of light and a curved mirror for reflecting the light passed through the Fabry-Perot filter.

The Fabry-Perot filter is an element filtering out and transmitting through a band of wavelength according to an incident angle, and the wavelength of the light transmitted through this filter is related to the incident angle of the filter by the equation,  $\lambda=\lambda_0 \cos \theta$ . Here,  $\lambda_0$  is the wavelength of the light incident vertically to the filter.

The Fabry-Perot filter is designed to give a narrow spectrum bandwidth enough to allow lasing on single cavity mode with an acceptable SMSR. The curved mirror is designed to reflect back the transmitted light through the Fabry-Perot filter along the same path as that of the incoming light. In order to remove the light reflected from the front surface of the Fabry-Perot filter, the waveguide of laser cavity is bended by an appropriate angle and radius of curvature.

The electrode array can continuously change the propagation direction of the light beam in the cavity by applying electric field or currents. The waveguide under the electrode array is fanned out to allow the shift of propagation direction of light.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a tunable semiconductor laser 1 according to the preferred embodiment of the present invention.

FIGS. 2A and 2B shows an example of an electrode array in FIG. 1.

FIGS. 3A, FIG. 3B, FIG. 3C show examples of manufacturing an output mirror in FIG. 1.

FIG. 4 is a cross sectional view illustrating an example of actually implementing the tunable semiconductor laser in FIG. 1.

FIG. 5 is an example that a Fabry-Perot filter and a curved mirror are formed in the semiconductor part in FIG. 1.

FIG. 6 is a cross sectional view of the curved mirror and the Fabry-Perot filter.

FIGS. 7A to 13B show the process of manufacturing the tunable semiconductor laser according to the embodiment of the present invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

Hereinafter, the embodiments of the present invention will be explained with reference to the accompanying drawings. However, the embodiment of the present invention can be changed into a various type, and it should be not understood that the scope of the present invention is limit to the following embodiments. The embodiments of the present invention are provided in order to explain the present invention to those skilled in the art.

## First Embodiment

FIG. 1 shows a tunable semiconductor laser 1 according to a first embodiment of the present invention. The tunable semiconductor laser 1 comprises a semiconductor part and a dielectric part. The semiconductor part includes an active area 14 and an electrode array 18 of the common semiconductor laser. It can include a phase control area 15 and an output mirror 16. The dielectric part includes a Fabry-Perot (FP) filter 13 and a curved mirror 17. Antireflection thin film 11 can be also included between the Fabry-Perot filter 13 and a facet of semiconductor. The antireflection thin film 11, the Fabry-Perot filter 13, and the curved mirror 17 can be manufactured by using dielectric material and growing it on one facet of the semiconductor block.

The Fabry-Perot filter 13 is an element of filtering an optical beam having a different wavelength according to an incident angle, and the wavelength of the light transmitted through this filter is related to the incident angle of the filter by the equation (1).

$$\lambda = \lambda_0 \cos \theta \quad (1)$$

Here,  $\lambda_0$  is the wavelength of the light incident vertically to the filter. The material of Fabry-Perot filter 13 is not specially limited and can be variously implemented if it can perform the function of the above-mentioned filter. For example, it can be manufactured by using  $\text{TiO}_2/\text{SiO}_2$  thin films by multiple periods of 180 nm/200 nm. In addition, it can also be manufactured by using a silicon oxide film and a silicon nitride ( $\text{SiN}_x$ ) film.

The Fabry-Perot filter 13 is designed to give a narrow spectrum bandwidth enough to allow lasing on single cavity mode with an acceptable SMSR. The curved mirror 17 is designed to reflect back the transmitted light through the Fabry-Perot filter 13 along the same path as that of the incoming light. In order to remove the light reflected from the front surface of the Fabry-Perot filter 13, the waveguide of laser cavity is bended by an appropriate angle and a radius of curvature.

The curved mirror 17 can be formed together with the Fabry-Perot filter 13 by a continuous process, and any available technique can be used in the spherical shape of the mirror. The curved mirror 17 reflects the light along the same path of the incident light. The same material used for the Fabry-Perot filter 13 can be used for the curved mirror.

The light beam is guided by the waveguide 12, which is bended by an appropriate angle  $\theta_1$  and radius of curvature  $r_1$ . Specific values of  $\lambda_1$ ,  $r_1$  can be determined by the core and the cladding materials of the waveguide and the angle  $\theta_1$  must be large enough to remove the reflected light from the front surface of the Fabry-Perot filter 13 and the radius of curvature  $r_1$  also must be large enough to minimize the loss of the light guided by the bending. For example, it is preferable that the angle  $\theta_1$  is larger than the critical angle that the reflected light from the Fabry-Perot filter 13 escapes

out of the waveguide. In case where the waveguide is composed of InGaAsP core and InP cladding and the index difference is  $\Delta n=0.189$ , the critical value is  $9.7^\circ$ .

The electrode array 18 can continuously change the propagation direction of the light beam in the cavity by applying electric field or currents. That is, the incident angle and the emergent angle of one electrode (for example, one triangle) of the electrode array 18 are different from each other, and the inside of the triangle is designed to have a refractive index different from that of the outside thereof by applying the electric field or the currents. By this principle, the propagation direction of the light beam can be changed. For example, the electrode array 18 can be a triangle, a trapezoid, or a polygon having two sides that are not parallel. The waveguide under the electrode array is fanned out to allow the shift of propagation direction of light. This will be explained later in detail. However, if the above-mentioned principle can be applied to the structure, the shape of the unit electrode in the electrode array 18 can be changed variously.

FIGS. 2A and 2B show the embodiments of the electrode array. FIG. 2A shows the triangular electrode 31 and FIG. 2B shows the reversed image of FIG. 2A. In FIGS. 2A and 2B, the light beams are shifted in opposite direction to each other. The electrode having various shapes such as trapezoid as well as the triangle can be designed, and such designed shapes should be included in the present invention.

On the other hand, the active area 14, the phase control area 15, and the output mirror 16 constituting the semiconductor part are components used in the common semiconductor laser and thus the explanation thereof will be omitted for convenience.

The output mirror 16 of the laser cavity can be formed at one facet of the semiconductor laser of FIG. 1, and can be formed in various methods designed specially to ensure the enough wide bandwidth. Also, in case where a semiconductor optical amplifier (SOA) is integrated with the semiconductor laser, various kinds of the output mirrors 16 can be introduced, in stead of the simple facet. FIGS. 3a, 3b, and 3c show the examples of output mirror 16 at the end of the semiconductor laser.

FIG. 3A shows a dielectric mirror 16 coated at one facet of the semiconductor laser.

FIG. 3B shows a uniform grating engraved in the curved waveguide 42 and FIG. 3C shows a chirped grating 43 engraved on a straight waveguide, both of which are deigned to cover the whole bandwidth of the tuning spectrum. As expected from the figures, the structure of FIG. 3B has an advantage of easy process using holographic lithography, and the structure of FIG. 3C has advantages of the simple straight waveguide and its smaller loss, but has a shortcoming that must use a slow process of E-Beam lithography.

Hereinafter, the operating principle of the tunable semiconductor laser 1 will be explained with reference to FIG. 1 in detail.

First, the light beam generated at the active area 14 is guided along with the waveguide 12. In case where the waveguide 12 is bended by the angle  $\theta_1$  of  $15^\circ$ , the angle  $\theta_2$  required for the tuning of 70 nm is calculated to about  $22.7^\circ$ , and thus the angle,  $7.7^\circ$  is enough to tune 70 nm of wavelength. Supposed that the core of the waveguide 12 is composed of the material of InGaAsP having the refractive index of  $n=3.359$  and the cladding thereof is composed of InP and the index difference between the core and the cladding is  $\Delta n=0.189$ , then the critical angle is about  $9.7^\circ$ . The reflected light from the Fabry-Perot filter is escaped out of waveguide and the bended angle  $\theta_1$  ( $15^\circ$ ) of the waveguide is enough larger than the critical angle.

On the other hand, supposed that the largest index change is  $0.516\%=(1558\text{ nm}-1550\text{ nm})/1550\text{ nm}$  at the highest electric current, the propagation angle shift is calculated to  $\Delta\theta=0.2965^\circ$  each time passing one electrode through a hypotenuse of the triangle having the angle of  $45^\circ$ . The number of the electrodes for the shift of  $7.7^\circ$  is 26 and, in case where the height of the first triangle is  $2\text{ }\mu\text{m}$ , the total length of the electrodes is  $315\text{ }\mu\text{m}$  and the height of the last triangle is  $57\text{ }\mu\text{m}$  by the computer calculation. These values are capable of implementing by the semiconductor process.

Next, the shifted light beam is incident to the Fabry-Perot filter **13**. The Fabry-Perot filter **13** is the element of filtering the different wavelength according to the incident angle. The wavelength of the light beam according to the incident angle of the Fabry-Perot filter **13** is as follows:

$$\lambda=\lambda_0 \cos \theta$$

Here,  $\lambda_0$  is the wavelength of the light beam incident vertically to the filter.

The light beam having the wavelength selected as mentioned above is reflected back along the path equal to that of the incident light by the spherical shape of the dielectric mirror **13**. By this method, the laser in the cavity oscillates between the output mirror **16** and the curved mirror **13**.

Hereinafter, an example of manufacturing the tunable semiconductor laser **1** according to a preferred embodiment of the present invention will be explained. FIG. **4** is a cross sectional view of the semiconductor laser of FIG. **1** and shows a cross section bended along with the waveguide.

First, an n-InP buffer layer **22** is grown on the n-InP substrate **21** by a thickness of, for example,  $3000\text{ }\text{\AA}$ , and then a waveguide **23** and a multiple quantum well (MQW) active layer **24** are grown on the buffer layer consecutively. The waveguide **23** is a mono-layer having a thickness of  $2000\text{--}4000\text{ }\text{\AA}$  and using quaternary such as InGaAsP, and the active layer **24** is composed of a multiple quantum well structure using the quaternary such as InGaAsP and has a thickness of  $2000\text{--}4000\text{ }\text{\AA}$ . Next, the active layer **24** is patterned by using a series of lithography and etching processes and then the waveguide **23** is also patterned with the bended structure.

Subsequently, a InP P-cladding layer **25** and a P-InGaAs layer **26** for an ohmic contact are deposited and then ion injection process is performed in order to isolate electrically the waveguide area from the surrounding area.

Next, the electrode array and the active area are separated and then Pi/Pt/Au films are deposited by thicknesses of  $200/200/3000\text{ }\text{\AA}$ , respectively, to form a metal electrode **27**. The kind of metal being capable of forming the electrode array is not specially limited and can be implemented variously. For example, gold (Au) can be deposited by a thickness of  $100\text{--}200\text{ nm}$ .

Next, the Fabry-Perot filter **13** can be mounted on one facet of the laser after performing the all the processes of the semiconductor part. Preferably, an antireflection thin film **11** is formed on the facet. And then the curved mirror **13** is formed on the Fabry-Perot filter **13**, which can be manufactured by the method such as high power laser cutting or wet etching after patterning by using the lithography. The curved mirror is also manufactured with a spherical shape along the vertical direction.

#### Second Embodiment

FIG. **5** shows the tunable semiconductor laser **1** according to the second embodiment of the present invention. The difference from the first embodiment is that both the Fabry-

Perot filter and the curved mirror are monolithically manufactured in the semiconductor part. FIG. **6** is a cross sectional view of the tunable semiconductor laser in FIG. **5**.

In this case, the fabrication is much easy and the radius and the center of curvature of the spherical mirror can be accurately adjusted by the lithography process.

Referring to FIG. **6**, the Fabry-Perot filter (**44** of FIG. **5**) is formed by periodically engraving the grooves having a specific width in the waveguide **23** and filling them with the material (**46** of FIG. **6**) having the refractive index different from that of the cladding or the core of the waveguide. For example, the grooves of few  $\mu\text{m}$  are formed in the InP cladding layer **25** and material (for example, a dielectric material such as a silicon nitride film or a silicon oxide film) having the refractive index different from that of the cladding layer **25** is filled in the grooves. The depth, the width, and the number of the grooves are variously selected according to the characteristics of the filter and are not specially limited. In addition, the material filling the groove can be variously selected according to the characteristics of the process and any material is included in the present invention.

In case of filling the silicon nitride film in the groove of the Fabry-Perot filter (**44** of FIG. **5**), the thickness (width) of the InP cladding layer is  $170\text{--}200\text{ }\mu\text{m}$ , and the thickness of the silicon nitride film is about  $300\text{ nm}$ . When defining one InP cladding layer and one silicon nitride film as a pair,  $5\text{--}10$  pairs are successively arranged to form a front or back mirror of the Fabry-Perot filter and two mirrors are spaced from each other with a predetermined interval. The predetermined interval is designed to perform the function of the Fabry-Perot filter, and can be set to, for example, half wavelength or 1.5 times the half wavelength.

The curved mirror **47** in FIG. **6** can be formed on the waveguide **23** by using the lithography and etching processes and depositing the gold or multi-layers of dielectric material.

Hereinafter, the example of manufacturing the tunable semiconductor laser **1** according to the second embodiment of the present invention will be explained with reference to FIGS. **7A** to **13B**.

Referring to FIGS. **7A** and **7B**, an n-InP buffer layer **22** having a thickness of  $3000\text{ }\text{\AA}$  is grown on an n-InP substrate **21** and then a core layer **23** having a thickness of  $2000\text{--}4000\text{ }\text{\AA}$  is grown on the buffer layer by using quaternary such as InGaAsP. And then, multiple quantum wells of active layer **24** composed of, for example, the material of InGaAsP is consecutively formed by a thickness of  $2000\text{--}4000\text{ }\text{\AA}$ . Then, the active area having the bended structure is formed by using an active area mask shown in FIG. **7b**. The detail process can use the common lithography and etching processes.

Referring to FIGS. **8A** and **8B**, the core layer **23** is patterned by using the lithography process to define the core area of the waveguide. As shown in FIG. **8b**, it has the shape designed to form the Fabry-Perot filter and the curved mirror near the end of the waveguide.

Referring to FIGS. **9A** and **9B**, a P-cladding layer **25** of the InP material is formed over all the structure by a thickness of about  $2\text{ }\mu\text{m}$  and then a P-InGaAs **26** layer for ohmic contact is grown thereon. Next, ion injection process is performed by using the mask of FIG. **9B**.

Referring to FIGS. **10A** and **10B**, the Fabry-Perot filter area A, the electrode array area B, the active area C, and the phase control area D are separated from each other by the isolation process. FIG. **10B** shows the mask pattern upon performing this process. The electrode array area B is formed with a triangle shape.



Referring to FIG. 11, the Fabry-Perot filter 44 is formed by periodically engraving the grooves having a specific width in the waveguide 23 and filling them with the material 46 having the refractive index different from that of the core or cladding, as mentioned above. The fine patterning process can be performed by using holography lithography.

Referring to FIG. 12, the curved mirror 47 having the section shown in FIG. 6 can be formed on the waveguide 23 by the lithography and etching process using the etch-preventing film 40 as a mask. The curved mirror 47 can have the gold film or multi-layers of dielectric material at the edge. In addition, the depth of the curved mirror 47 is not specially limited and can be deep to the buffer layer 22, the core layer 23, or the cladding layer 24.

Referring to FIGS. 13A and 13B, the electrodes are formed on an appropriate position of the structure. FIG. 13B shows the pattern mask for forming the electrode. The electrodes are formed on the electrode array area B, the active area C, and the phase control area D as shown in FIG. 13a. As the electrode materials, Pt/Pt/Au films may be deposited by thicknesses of 200/200/3000 Å to form the metal electrode 27.

Accordingly, as mentioned above, the present invention can accomplish the above-mentioned objects. That is, the tuning is successively accomplished over the wide wavelength band. High output powers and fast tuning time can also be expected.

Although the present invention has been illustrated and described with respect to exemplary embodiments thereof, the present invention should not be understood as limited to the specific embodiment, and it should be understood by those skilled in the art that the foregoing and various other changes, omission and additions may be made therein and thereto, without departing from the spirit and scope of the present invention.

What is claimed is:

1. A method of manufacturing a tunable semiconductor laser, comprising the steps of:

forming a buffer layer of a lower cladding layer, a core layer of a waveguide, and an active layer on a substrate; patterning said core layer and said active layer to form an active area for generating a light beam and a curved core layer for guiding said light beam on a portion of said waveguide;

depositing an upper cladding layer and an ohmic layer over all the structure;

injecting ions to isolate said waveguide area from surrounding area;

forming electrodes including an electrode array for shifting the propagation direction of the light beam transmitted through said waveguide by applying electric field or currents to a predetermined portion of said waveguide to;

sequentially forming a Fabry-Perot filter and a curved mirror on one facet of said semiconductor laser;

wherein said Fabry-Perot filter filters only the light beam having one wavelength selected according to the shift of the propagation direction of said light beam by said electrode array, and said curved mirror reflects the light beam having said wavelength passed through said Fabry-Perot filter.

2. The method according to claim 1, wherein said Fabry-Perot filter is formed of  $\text{TiO}_2/\text{SiO}_2$  or  $\text{SiN}_x/\text{SiO}_2$  thin films.

3. The method according to claim 1, further comprising an antireflection film between said Fabry-Perot filter and said facet of semiconductor.

4. A method of manufacturing a tunable semiconductor laser, comprising the steps of:

forming a buffer layer of a lower cladding layer, a core layer of a waveguide, and an active layer on a substrate; patterning said core layer and said active layer to form an active area for generating a light beam and a curved core layer for guiding said light beam on a portion of said waveguide;

depositing an upper cladding layer and an ohmic layer over all the structure;

injecting ions to isolate said waveguide area from surrounding area;

etching a group of grooves having a uniform interval and depth in said upper cladding layer of an area of said waveguide and filling them with dielectric material having a refractive index different from that of said upper cladding layer to manufacture a Fabry-Perot filter;

forming a curved mirror on the edge of said Fabry-Perot filter; and

forming electrodes including an electrode array for shifting the propagation direction of the light beam transmitted through said waveguide by applying electric field or currents to a predetermined portion of the waveguide between said Fabry-Perot filter and said active area,

wherein said Fabry-Perot filter filters only the light beam having one wavelength selected according to the shift of the propagation direction of said light beam by said electrode array, and said curved mirror reflects the light beam having said wavelength passed through said Fabry-Perot filter.

5. The method according to claim 4, wherein said curved mirror is formed with metal or dielectric material on the side of said Fabry-Perot filter so as to reflect the light beam transmitted through said Fabry-Perot filter.

6. The method according to claim 4, wherein said dielectric material having refractive index different from that of said upper cladding layer is a silicon nitride film.

7. The method according to claim 1, wherein one electrode of said electrode array has an incident angle and an emergent angle different from each other, the inside of said electrode has a refractive index different from that of the outside thereof by applying the electric field or currents.

8. The method according to claim 1, further comprising the step of forming a phase controller on the other side of said active area.

9. The method according to claim 1, further comprising the step of coating a reflection film on said curved mirror.

10. The method according to claim 1, further comprising the step of manufacturing an output mirror for outputting the light beam transmitted through said waveguide on the other side of said active area.

11. The method according to claim 1, wherein said output mirror includes a uniform grating engraved in the curved waveguide or a chirped grating engraved in a straight waveguide.